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Aerodynamics of Blended Wing Body (BWB) Unmanned Aerial Vehicle (UAV) Using Computational Fluid Dynamics (CFD)

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ABSTRACT

A thorough understanding of the aerodynamic behaviour of Blended Wing Body (BWB) aircraft is important because of its high lift to drag ratio. The use of Computational Fluids Dynamics (CFD) has accelerated aerodynamic analysis of BWB aircraft. Steady-state, three-dimensional CFD calculations were made of the BWB model using the Spalart-Allmaras turbulence model. Comparisons of aerodynamic characteristics such as lift coefficient, drag coefficient, pitching moment coefficient, pressure contours and Mach number contours were made both of two-dimensional aerofoil sections in the BWB model and a complete three-dimensional model. The lift coefficient distributions along the body and wing span were analyzed. The effect of changing the angles of attack and aerofoil profiles were investigated. The BWB design presented here has achieved an unprecedented capability in terms of sustainability of flight at high angle of attack, low parasite drag coefficient, efficient thrust required at optimum flight speed and acceptable margin of centre of gravity for trimmed flight at optimum speed without control surface interference.

Keywords: *Aerodynamics, Subsonic, Unmanned Aerial Vehicle, Computational Fluids Dynamics*

Introduction

Blended wing body (BWB) is a hybrid of a flying-wing aircraft and a conventional aircraft. BWB is a concept where fuselage, wing and tail are merged together as a single entity [1]. The body is designed to have a shape of an airfoil and is carefully streamlined with the wing. Its advantage is that the fuselage that generates lift together with the wing thus increasing the effective lifting surface area. In conventional aircraft, the wing is the main contributor to the generation of lift. The primary function of the fuselage is to support the payload and connect the wing and tailplane (or canard fore plane) together. Therefore the fuselage contributes a large amount of profile drag without generating much lifting force. The maximum L/D ratio depends on the ratio of the aircraft span to the square root of the product of the induced drag factor and the zero-lift drag area, which is proportional to the wetted area of the aircraft. The larger span, small wetted area, and lower skin friction (resulting in less drag) of BWB aircraft gives a high aerodynamic performance [2][3]. The slow evolution of fuselage-to-wing thickness by careful design may suggest that more volume can be stored inside the BWB aircraft, hence increasing the payload & fuel capacity [1][4][5].

The BWB concept owes much from flying wing research by German designer Arado, who designed the AR E.555 long-range flying wing strategic bomber in 1943 to enable Luftwaffe (German Air Force) to strike main cities in Europe. In this design the fuselage had the same diameter as the wing root's thickness. The large wing root thickness enabled 4000 kg of bombs to be carried inside the fuselage-wing. Its low drag configurations enabled the E.555 to travel 5000 km with internal fuel only [6]. In the same era, American engineer Jack Northrop proposed an all-wing aircraft. Amongst his great achievements were the B-35 medium bomber driven by piston aero-engine and the B-49 long range strategic bomber driven by turbojet engines. However, B-49s were withdrawn from United States Air Force (USAF) service due to stability problems (replaced by conventionally-configured B-52 bombers) [7].

It was not until 1981 (just before the death of Jack Northrop) that the USAF contracted Northrop Corporation to design and produce a flying wing strategic bomber known as B-2 Spirit. Using a modified supercritical transonic airfoil for its wing section, the B-2 can achieve transonic speed at the range of 9,600 km undetected by radars [8]. The stability problems inherent to flying-wing design was rectified by use of a new digital flight control system. Since then research has been conducted in BWB aerodynamics and stability and some of the works are reported in references [8] and [9].

Multidisciplinary Design Optimisation (MDO) has been developed to tackle various problems related to BWB design. Optimisations involve determination of which design has the best performance (i.e range), highest lift generation, best stability and control characteristics, lightest structural design and lowest propulsion thrust required [4][9][10]. In the United States, Wakayama and Kroo developed the WINGMOD algorithm which uses the vortex-lattice method to calculate the drag profile across the span and maximum lift [9]. The process starts with configuration of BWB through preliminary design procedure to establish a baseline wing-body shape and sizing. From there, WINGMOD generates an optimised design. CFD analysis confirms that less drag and more lift can be generated by the new design. The algorithm is further improved with the use of Navier-Stokes equations.

Development of optimised aerodynamics for BWB in Europe focused on the objective of designing a commercial BWB airliner to be produced by Airbus Industrie. The stability and structural problems must be identified early in the preliminary design stage because the wings of a BWB cannot be moved later without a significant change in the body design. The preliminary Aircraft Design And Optimisation Programme (PrADO) algorithm was developed which used the Lifting-Line Theory to optimize the initial weight/lift. The Higher-Order Subsonic/Supersonic Singularity Method was used to predict the induced drag and the linear potential low solution. The drag coefficient was then calculated based on circulation distribution in spanwise direction and the downwash in the Treffilz plane [5].

Other research by Qin et al. involve computing the ideal aerodynamic performance of baseline configurations followed by viscous flow simulation [1]. These include the effect of spanwise distribution on BWB through an inverse twist approach that combines the low-fidelity Panel Method and the high-fidelity Reynolds-averaged Navier-Stokes Solution Method. The BWB is mapped to an airfoil optimisation problem and the airfoil is projected back to the BWB wing. The result is a high aspect ratio BWB aircraft design that has a lower surface area to volume ratio thus lower friction drag and induced drag compared to conventional aircraft. Since the planform area that effectively generates lift is increased it can sustain flight at lower speed without stall.

BWB aircrafts have also been studied extensively by Phantom Works of Boeing who built and tested a 17 ft remote controlled model followed by a larger 35 ft X-48 UAV. It flew successfully in series of flight tests in 2004 [11].

The research reported in this paper will focus on an aerodynamic analysis of a BWB planform for the development of a UAV. The basic analysis focuses on aerodynamic characteristics such as lift coefficient at each spanwise location, spanwise lift distribution, overall lift coefficient, drag coefficient, centre of pressure and centre of aerodynamics. The BWB planform is modeled in CATIA to obtain smooth 3-dimensional unification of wing and body and then meshed into Computational Fluid Dynamic (CFD) models. The CFD simulation was determined using a CFD software, FLUENT. The use of CFD enables visualization of flow and pressure distribution on the surface of the BWB model.

The main objective of this study was to obtain the aerodynamic characteristics such as lift coefficient, drag coefficient and pitching moment coefficient for 3D model of blended wing body (BWB) UAV aircraft. The analysis was conducted at 0.3 Mach number (low subsonic flow). The study also analyzed the change in aerodynamic characteristics with respect to incidence by performing simulation at various angles of attack.

Research Methodology

The development of a computational model began by deriving geometrical equations to describe the BWB planform. Parameters such as wing planform area, sweep angle, taper ratio for each section (body, inner wing and outer wing), and the span and chord for various spanwise locations were determined for each configuration. These mathematical models were then translated into a 3D drawing in CATIA, where the sizing of each aircraft's planform configuration is taken relative to wing span. Figure 1 shows a CAD model of proposed design of BWB UAV.

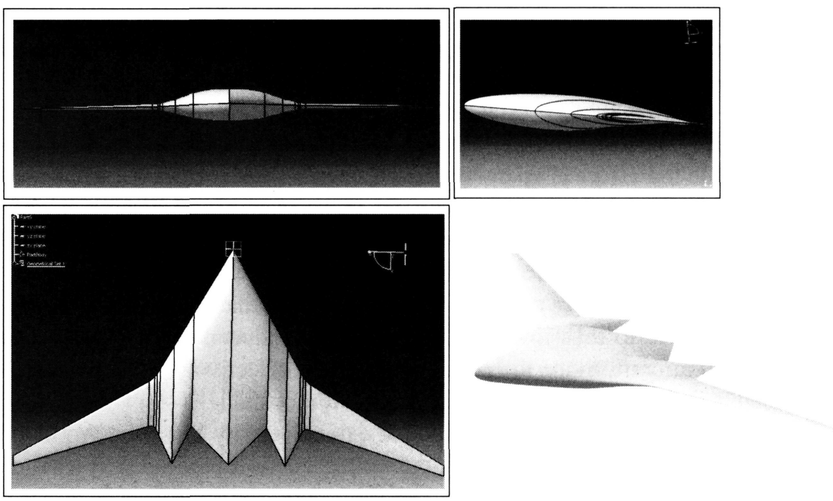

Figure 1: CAD Model of BWB UAV (Three View and 3D)

The second stage involves meshing the CATIA CAD model into elements in the FLUENT CFD code. Boundary conditions and airflow are defined. The pressure distribution on the surface of the BWB UAV is calculated which allows determination of aerodynamic characteristics of BWB such as CL, CD and CM at various angle of attack. Fluent allows visualisation of the airflow around the BWB to recognise critical areas to focus on vortex reduction to improve the design. Figure 2 shows the CFD meshing of the BWB in Fluent that consists of 800,000 elements.

Result and Discussion

Simulations of the BWB UAV were carried out at various angles of attack (α between -3° to 39°). For each α the stall angle and the lift-to-drag ratio can be determined to predict the best cruising angle of attack for this BWB model.

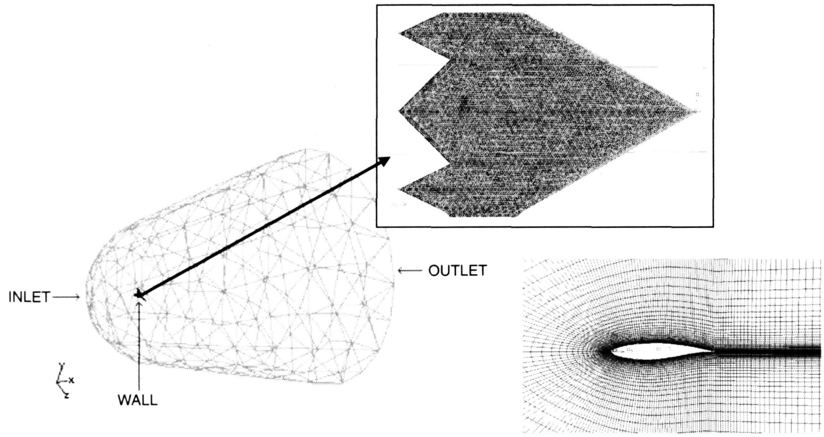

Figure 2: CFD Mesh in Fluent. Large Conic Area of Inlet-Outlet Air with Respect to the Size of Aircraft (left) is then Further Refined with Very Fine Mesh Size on the BWB Airframe (right). Side View of the BWB Mesh is Shown on the Right-Bottom

Lift Coefficient, C_L Analysis

Figure 3 shows that the lift coefficient, C_L changes with the angle of attack, α. The figure shows that at zero angle of attack, there is already a lift coefficient, 0.13 (which is a common characteristic of most cambered aerofoils). The lift coefficient, C_L reaches a maximum at 35° with $C_L = 1.03$, which indicates that the stall angle is 35°.

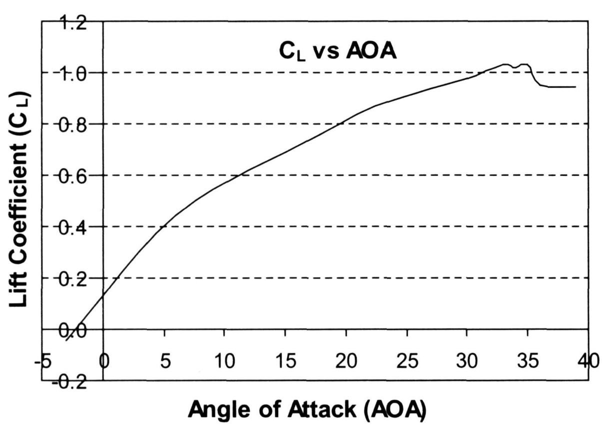

Figure 3: Lift Coefficient, C_L Versus Angle of Attack, α Graph

Drag Coefficient, C_D Analysis

From the graph of drag coefficient C_D, versus angle of attack á, in Figure 4, minimum value of drag can be found at slightly less than 0 degree angle of attack and increases slowly until 6 degrees. Steeper rise in drag coefficient is observed after 6 degrees indicating the parabolic nature of this drag polar. However, the increase becomes slightly linear (especially after 15°).

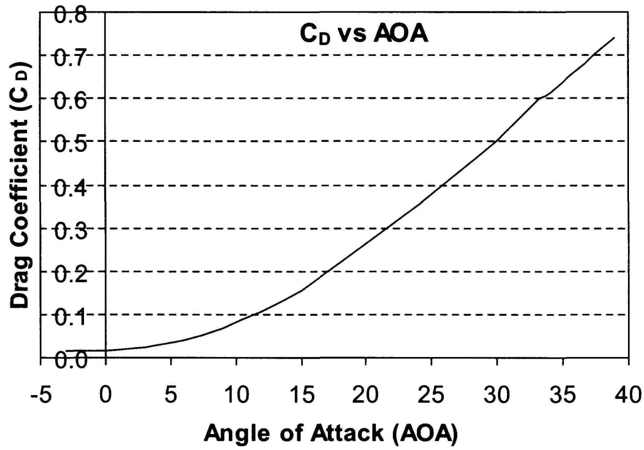

Figure 4: Drag Coefficient, C_D Versus Angle of Attack, α

Pitching Moment Coefficient, C_M Analysis

Figure 5 shows aircraft pitching moment coefficient versus angle of attack. It shows a positive slope of moment curve. From the graph the pitching moment data starts at about -3° and the graph increases rapidly until 3° in an almost linear manner. After that, the increment of C_M slows down until 12° and then starts to increase linearly again until 39°.

Lift-to-drag Ratio Analysis

Figure 6 shows the lift-to-drag ratio of the 3D BWB model. Its highest value is 12.2 at a 3° angle of attack. This is much lower than the value of 50.2 collected from 2D analysis of this design using X-FOIL software (for invisid flow on the RAE2822 airfoil that forms the base of BWB wing section). The value of the maximum lift-to-drag ratio on this figure suggests that the best cruising speed for the minimum thrust required occurs at a speed corresponding to a 3° angle of attack, where the lift to drag ratio is 12.2. By comparison a BWB designed by a team of researchers from Cranfield University, has a maximum lift-to-drag ratio of 14 [1].

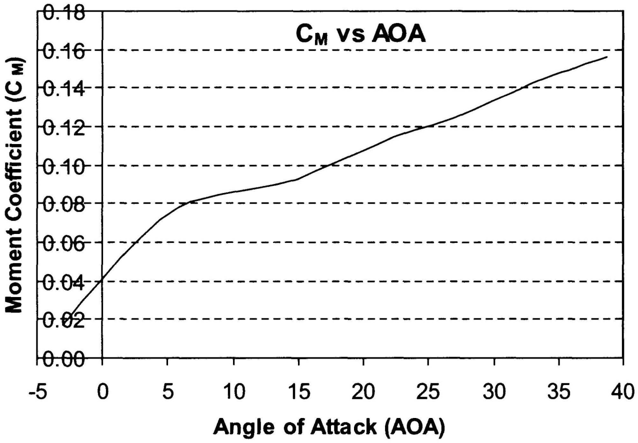

Figure 5: Pitching Moment Coefficient, C_M Versus Angle of Attack, α Graph

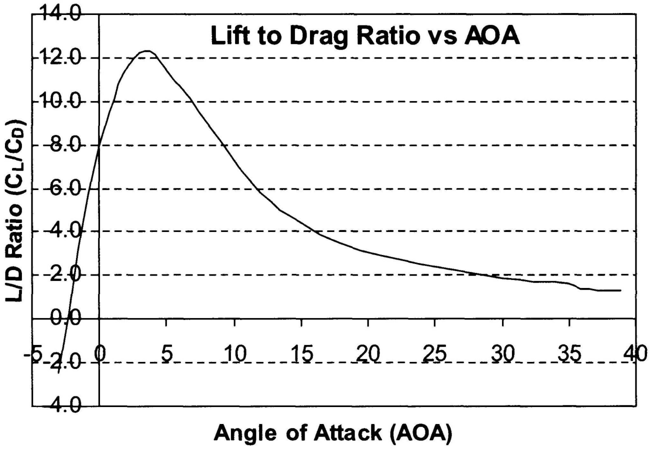

Figure 6: Lift-to-Drag Ratio, C_L/C_D Versus Angle of Attack, α

Lift Coefficient, C_L Versus Drag Coefficient, C_D Analysis

Figure 7 shows a slightly-distorted parabolic trend of drag polar (C_L vs C_D) up until the stall region. From this figure, C_{D0} is 0.0154. Cruising at the maximum lift-to-drag ratio will mean flying at minimum drag where $C_{Dmin} = 2C_{Do} = kC_L2 = 0.0308$. The lift coefficient at maximum lift-to-drag ratio of 0.38, is lower than the usual C_{Lopt} of 0.40-0.50 range. Taking into account that the maximum lift-to-drag ratio is 12.2, then this 200-kg BWB UAV may only need 16.4 kgf (161 N or 36 lbs) of thrust from both of its engines (around 80 N or 18 lbs of thrust each).

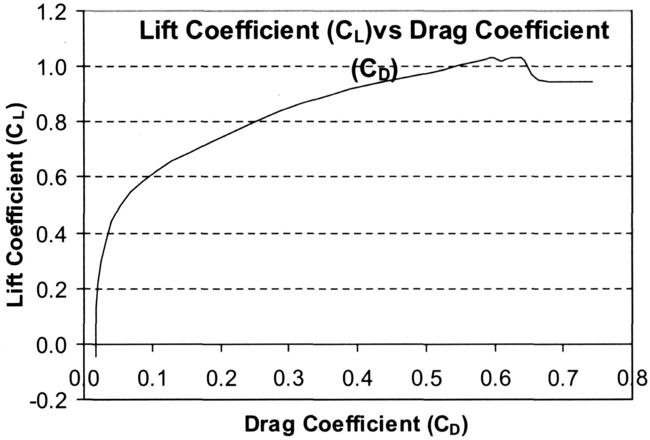

Figure 7: Lift Coefficient, C_L Versus Drag Coefficient, C_D Graph for 3D Model

Pressure Coefficient Contours

Upper and lower surface figures shown in Figure 8 and Figure 9 show that when the angles of attack, α increase, the upper surface will create a lower pressure coefficient, C_P. In Figure 8 the high-intensity blue area located on the upper surface suggests high lift (negative pressure/suction) is generated (low α with 7.4% force directed backward creating drag). In high angle of attack, Figure 9 shows that the BWB UAV is still capable of generating lift, however about 1/3 of the total force is directed backward (drag).

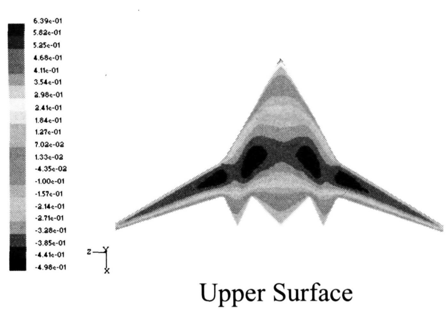

Figure 8: Pressure Coefficient Contours at $\alpha = 0°$

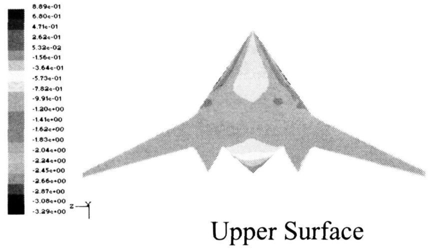

Figure 9: Pressure Coefficient Contours at $\alpha = 35°$

Mach Number Contours and Pathlines

Mach Number contours of upper and lower surfaces are shown in Figure 10 and Figure 11. Increasing angles of attack will cause the Mach number on upper surface to increase while simultaneously decreasing on the lower surface. This results in the lift coefficient increasing when angle of attack increases. As α increases more, the flow will eventually separate from the surface. Separation starts from the wing root and spreads towards the body and wing area. Figure 11 shows flow over the wings at the stall angle of 35°. Although the wing does not provide lift at this α, effective flow occurs on the center body resulting in some lift being generated by the high swept leading edge vortex on the body (similar to delta wing).

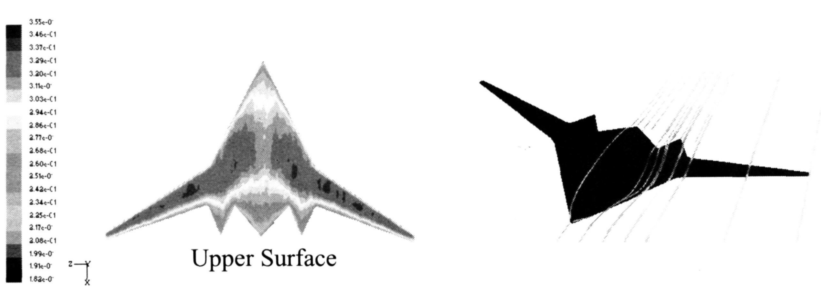

Figure 10: Mach Number Contour and Pathlines Contours at $\alpha = 0°$

Lift Distribution Along The BWB Span

Figure 12 shows the local lift coefficient along half span of BWB at L/D_{max}. The maximum local lift coefficient is 0.42 (at the 0.28 of half span of BWB). From the result, the BWB aircraft will first stall at this maximum local lift location and then expand towards the 0.2 section or body areas.

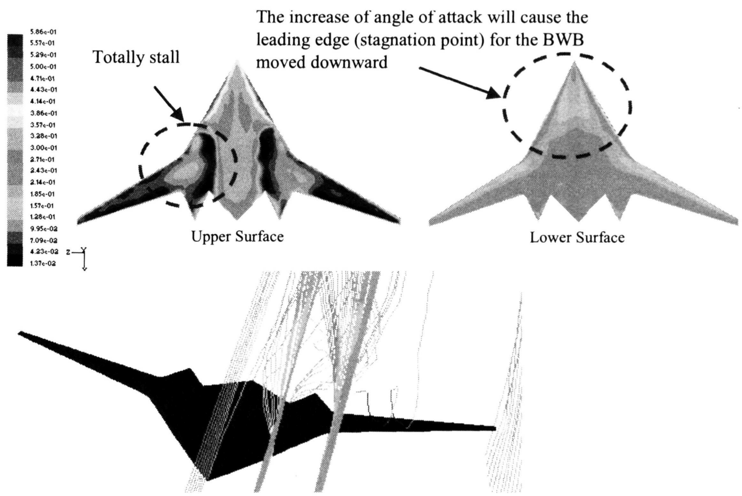

Figure 11: Mach Number Contours and Pathlines at $\alpha = 35°$ for Upper and Lower Surfaces

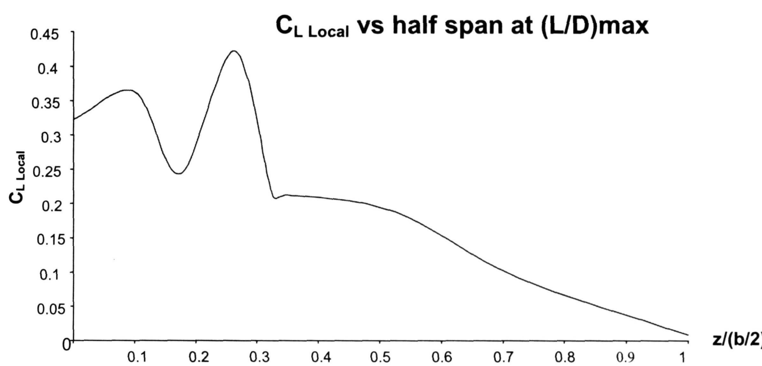

Figure 12: Local Loft Distribution Along BWB Half Span

Conclusion and Recommendations

This paper examines the aerodynamic characteristics (C_L, C_D, C_M) of 3D model of blended wing body (BWB) UAV aircraft using computational fluid dynamics. Flight simulations were conducted at Mach 0.3 for various angles of attack. This research found that the BWB UAV is capable of flying at up to 35° angle of attack without detrimental stall. At this angle of attack, the wing is already non-effective, but lift is provided by the body. However, the drag is very significant at this angle of attack. The ineffectiveness of the wing implies that the aileron control will not be effective anymore, hence problematic lateral control must be addressed in further research.

Future research should also focus on modifying the planform design to improve to improve the aerodynamic characteristics of the BWB (such as increasing L/D). The effect of the wing swept-angle also needs more investigation. The rear planform shape of the BWB must also be studied. The CFD results should also be validated with wind tunnel experiments.

BWB shaped aircrafts give promising advantages for the next generation of large commercial airliners and military aircraft. Due to its large volume capacity inside its blended fuselage (body), BWB is suited for carrying weapons, bulk sensors and huge amount of fuel. It is expected that the BWB UAV technology demonstrator prototype being designed (of four-metre span with 200-kg MTOW) in this analysis will have a potential radius of 300 to 400 kilometres equipped with basic flight computers and visual sensors.

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